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Microseismic Instrumentation Developments

A Tape-Triggering System and Energy Analyzer

By Bernard J. Steblay

UNITED STATES DEPARTMENT OF THE INTERIOR

(United States. Bureau of Mines)

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UNIT OF MEASURE ABBREVIATIONS USED IN THIS REPORT

dB	decibel	μF	microfarad
ft	foot	μs	microsecond
h	hour	ns	nanosecond
Hz	hertz	pct	percent
ips	inch per second	pF	picofarad
kHz	kilohertz	s	second
min	minute	V	volt

MICROSEISMIC INSTRUMENTATION DEVELOPMENTS

A Tape-Triggering System and Energy Analyzer

By Bernard J. Steblay[1]

ABSTRACT

Two instruments have been constructed that extend microseismic data collection and processing capability for Bureau of Mines research in rock burst, coal bounce and outburst, and roof fall monitoring. The first instrument is a 13-channel tape-triggering system. This system allows better utilization of instrumentation tape recorders by collecting data digitally, turning the tape on only when valid data are present, and increasing the dynamic range of the recorder by using digital data. A digital-to-analog converter is used to provide analog output of the recorded digital data. The instrument records a much larger time slice of transient events than do current commercial devices. The second instrument is a microseismic energy measurement device. This device uses recent developments in integrated circuits to overcome the dynamic range and accuracy limitations of previous instruments. The analog signal is converted to a digital one, and then high-speed multiplication techniques are used to square the amplitude value in real time and integrate it.

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INTRODUCTION

The first instrument addressed in this paper deals with the frequently encountered problem in data collection of recording analog data that consist of randomly occurring transient events. If an analog tape recorder is run continuously, it places time constrictions on the data collection and also requires laborious scanning of a long tape to find a few pieces of significant data. This problem occurs for the Bureau of Mines in collecting microseismic data. The tape-triggering system is a solution to these problems. It triggers the tape only when valid data are occurring, but because it first records the data in its solid state memory, it does not lose any pretrigger data. It can operate unattended for long periods since it requires servicing only when the tape fills up. It operates with ordinary frequency modulation (FM) analog recorders but greatly increases their dynamic range because of its digital encoding. Using 24,000-byte memory per channel allows long transients to be recorded.

The second instrument addressed deals with the data collection problem of determining the energy of an incoming analog signal. This energy estimation is a valuable piece of data for rock stability determination. Analog or quasi-analog approaches such as voltage-to-frequency conversion for acoustic emission measurement have serious limitations in dynamic range and accuracy (1).[2] The energy measurement system discussed in this report overcomes such limitations by using a fully digital processing approach.

TAPE-TRIGGERING SYSTEM

The tape-triggering device was conceived and specified by the Bureau of Mines Denver Research Center and designed and constructed under a Bureau contract (2). Its two major sections are the event recorder and control unit and the event reproducer unit (fig. 1). The units are designed to work with an FM instrumentation tape recorder with a minimum bandwidth of 40 kHz (3).

RECORDING SECTION

The event recorder and control unit first filters the incoming data using a low-pass filter set at either 1 or 10 kHz. The filtered analog signal is then converted to a 12-bit digital signal at an 83.3-kHz sample rate. The sample rate was chosen to provide good analog resolution at the output of the event reproducer even at the upper bandwidth of 10 kHz. The 12-bit resolution provides a total dynamic range for the bipolar input of greater than 70 dB, which exceeds the typical performance of an analog FM recorder by more than 16 dB.

The digitized amplitude values are then stored in a 294,912-bit (24,576-word) per channel memory. This large per channel memory allows the storage of nearly 0.3 s of signal in memory at any given time. This overcomes the time limitation caused by the short memories typically found in commercial transient recorders. The event that the author felt made such a device commercially practical was the development of 64,000-bit charge-coupled-device (CCD) shift register memories, but these could not be supplied in time for construction. Substituting 64K dynamic access memory proved satisfactory.

The memory of the event recorder is divided into pretrigger and posttrigger sections. Data are continually being recorded by the memory. As each new sample is collected, the previous sample is shifted one memory cell down the chain. The trigger criteria are controlled by a microprocessor. If a valid trigger occurs, the 2,500 samples that were collected just prior to the trigger are saved. The remaining 22,076 words of the

[2]Underlined numbers in parentheses refer to items in the list of references at the end of this report.

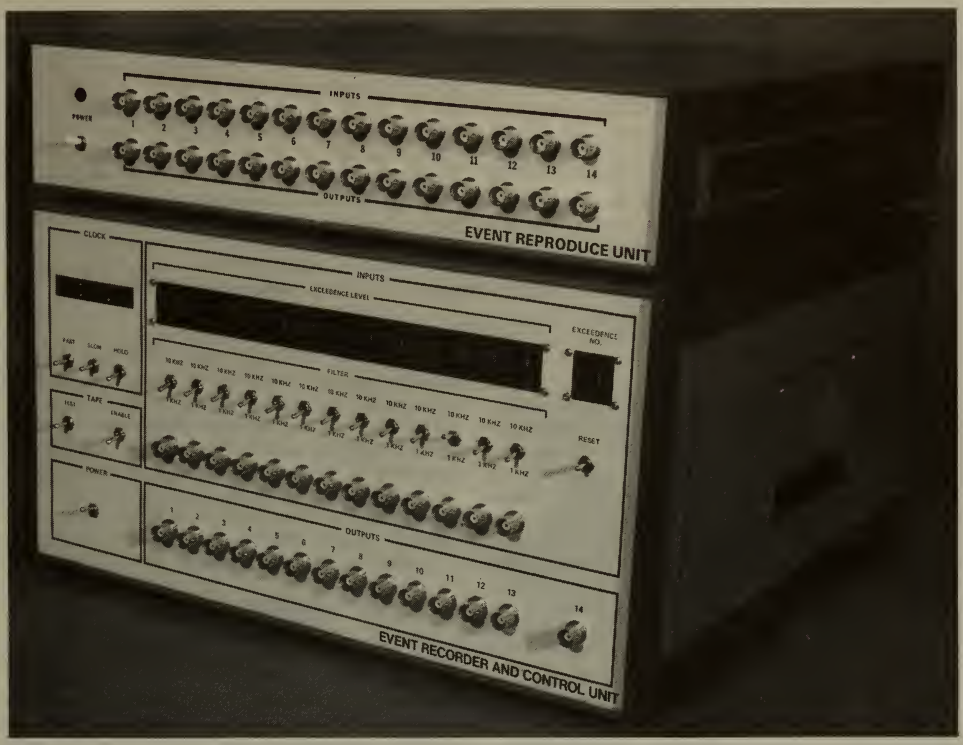
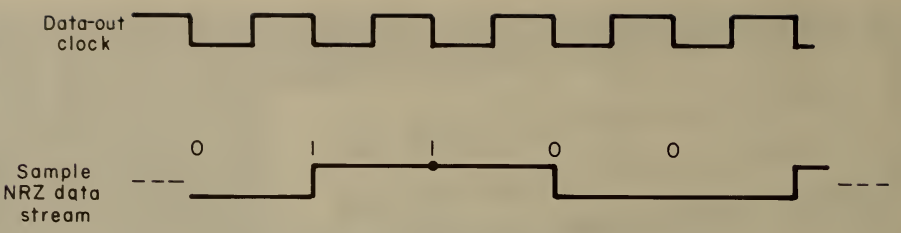


FIGURE 1. - Tape-triggering system and analog reproducer system.

memory chain are then filled with post-trigger data. Thus about 0.03 s of data prior to the trigger is saved for analysis. This information is often crucial for making first-arrival analyses.

The microprocessor controls both the threshold criteria and the valid event criteria. The threshold level is selected by front panel switches and ranges from 0.4 V to 2 V in 0.2-V increments. If the threshold level on any channel is exceeded, the event recorder begins recording all of the other channels simultaneously. When the memory chain is filled, the microprocessor determines whether enough channels exceeded their thresholds to constitute a valid event. This channel requirement number, which is settable from 2 to 5, insures that a spurious single event on one or more channels will not trigger the system. In the case of a mining application, a typical spurious event would be drilling near a geophone. Once it has been determined that sufficient channels have valid data, the recorder is remotely triggered. When the recorder tachometer indicates proper speed, or a 5-s default time is reached, insuring that proper tape speed has been reached, the 0.3 s of digital data for all channels are recorded on the tape.

The digital data are encoded for the FM tape using a digital standard nonreturn-to-zero (NRZ) signal clocked out at 40,000 Hz (fig. 2). Since each channel was sampled using a 12-bit-wide word 24,576 times, 294,912 bits must be written to the tape. The write time is



NOTE : NRZ format requires the dc levels of FM record.
Bi ϕ L format would have to be used with direct record.

FIGURE 2. - NRZ recording signal format.

then about 7.5 s. Each channel is written to its respective tape channel simultaneously. If the tape is initially stopped, the total time to accelerate to speed, write data, and decelerate to a stop is about 12 s. If a second transient or group of transients occurs before the tape is stopped, the transfer of data will, of course, occur in a much shorter time. The deadtime for an event lasting longer than the 0.3 s of memory is essentially equal to the 7.5-s write time.

The 14th channel is used to record the time of day and for providing clock pulses for later use by the output digital-to-analog converter. The time of day is written on the tape in a pulse-coded magnetic (PCM) format. The accuracy of this clock is ±1/2 s. The overall format is custom-designed for the needs of this system. The general operation of the recording side of the tape-triggering system is to digitize and record 13 channels of analog data. Frequency may be limited to 10,000 or 1,000 Hz at the user's option. The worst case situation occurs with a 10,000-Hz signal. Even here eight samples are taken per cycle, insuring good analog resolution. The system is designed to record transients, which appear on two to five channels minumum, as selected by the user, during the memory time window so that spurious recording is eliminated. The system is designed to record only valid data and pack them on the tape as densely as possible by operating the tape recorder only when good data have been received. A pretrigger history is retained so that signals may be studied prior to the point that they exceed the threshold. The time of day is also recorded with each valid event so that the time history of the tape is preserved. About 100 events can be stored on a 7,200-ft reel of tape.

REPRODUCING SECTION

Once the tape has been filled, or the desired period of monitoring is completed, the output section of the tape triggering and recording system may be used to reproduce the digitally recorded signals in analog form. The basic function of the output section is to read the digital signals from the tape and convert them to an analog output. The timing signals on channel 14 are used to control the digital-to-analog conversion rate so that the reproduced data look exactly like the recorded data. Fluctuations in tape speed or head skew will thus not degrade the data. The flexibility of the reproduction speeds on the tape recorder can be used to scale the analog output to match the speed of the recording device. One must, of course, keep track of these scaling factors so the proper time scale for the output records is known.

The reproducing section uses comparators to read the serial bit stream for each channel and shift registers to assemble these bits into 12-bit words. As each 12-bit word is assembled, it is

coupled to a digital-to-analog converter. After appropriate conditioning the analog signal for each channel is sent to its respective output connector, where it may be used to drive recording pens or oscillograph galvanometers. The output levels are ±10 V maximum. The present calibration factor is 1 V into the recording section equals 1.41 V out of the reproducing section. The pulse amplitude modulation type PCM format of the 14th channel contains a bit clock to operate the serial shift registers in the data channels, a word clock at one-twelfth the bit clock rate to operate the output latches, and the time of day information (fig. 3). The time of day is decoded and presented in a manner that is easy for the operator to read from graphic records. The output amplifier on the clock channel has only three possible states: -2 V, 0 V, or +2 V. Positive excursions are read as binary coded data (BCD) ones, and negative excursions as BCD zeros. The overall time of day output as seen on a graphic recorder displays the hours, minutes, and seconds of the occurrence (fig. 4).

The capacity of the tape system is being extended by implementing a biphase (BiϕL) encoding system as an option. This allows the use of direct recording, which means the tape can be run at much lower speeds for a given bandwidth. The NRZ data require the direct current (dc) levels provided by FM recording. By converting to biphase, the slower tape speed (15 ips) will at least quadruple the number of events that can be recorded per tape.

The specific parameters for the device discussed in this paper were chosen with a specific microseismic recording problem in mind (2). Most of these parameters are readily variable to suit other applications. The parameters were also restricted by the fact that the Bureau's recorders were already equipped with FM

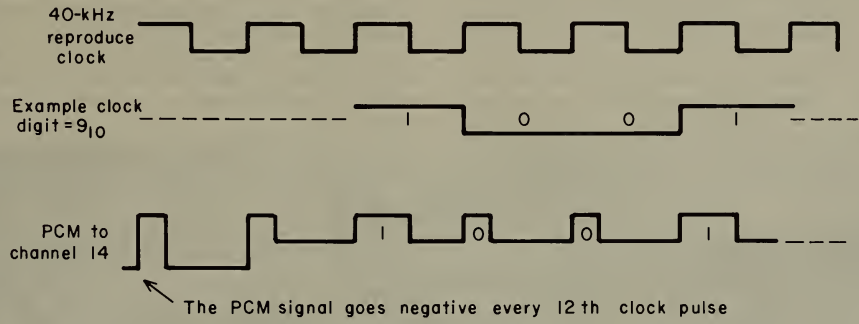
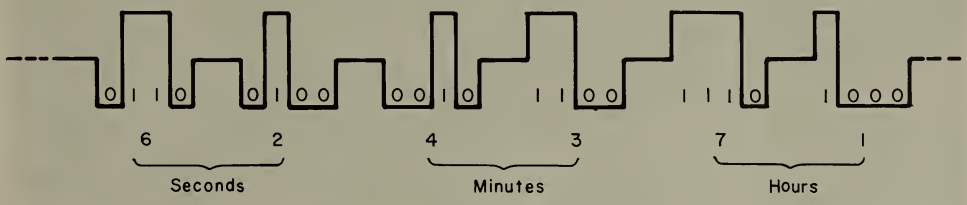


FIGURE 3. - Timing channel format.



Time = 17 h 34 min 26 s

FIGURE 4. - Time of day information as presented on output record.

electronics. There are obvious trade-offs between bandwidth and recording time. Total memory and prehistory memory length are obviously variable. By using direct-record electronics the record bandwidth could be greatly increased, though the coding would have to be changed to biphase since dc levels would be lost. Using direct record it is conceivable that a system with no dead time between events could be designed. The current system was designed to take advantage of recorders the Bureau already possessed and to maintain compatibility with the normal analog use of these recorders. The concept could be extended to use magnetic cartridge recorders or disc storage, though the system would have to be significantly modified.

ENERGY ANALYZER

The energy analyzer (fig. 5) was conceived and specified by the Denver Research Center of the Bureau of Mines. Design and construction were performed by the Rockwell International Energy Systems Group under a Bureau contract. Testing and final modification were performed by the Denver Research Center. The analyzer processes an externally supplied analog signal. On external command the unit measures the energy in a six-segment frequency distribution of the incoming signal. The processed data are then made available to an external minicomputer.

ANALOG-TO-DIGITAL CONVERSION

The analyzer uses six passive low-pass analog filters to separate the signal into bands of frequency of interest and insures that no signal aliasing occurs. The analog signal is then converted to a digital signal, squared, scaled, and integrated for a selected time period. The external minicomputer-based microseismic system is then used to trigger, read status and data, and reset the analyzer. The unit has a built-in self test. Data are also readable from a front panel light-emitting diode (LED) display.

The first stage of signal processing is to filter the analog signal. Filter bandwidths are each from near dc to 10 kHz, 1.6 kHz, 0.8 kHz, 0.4 kHz, 0.2 kHz, and 0.1 kHz. The 10-kHz section is a full-bandwidth filter for the Bureau's

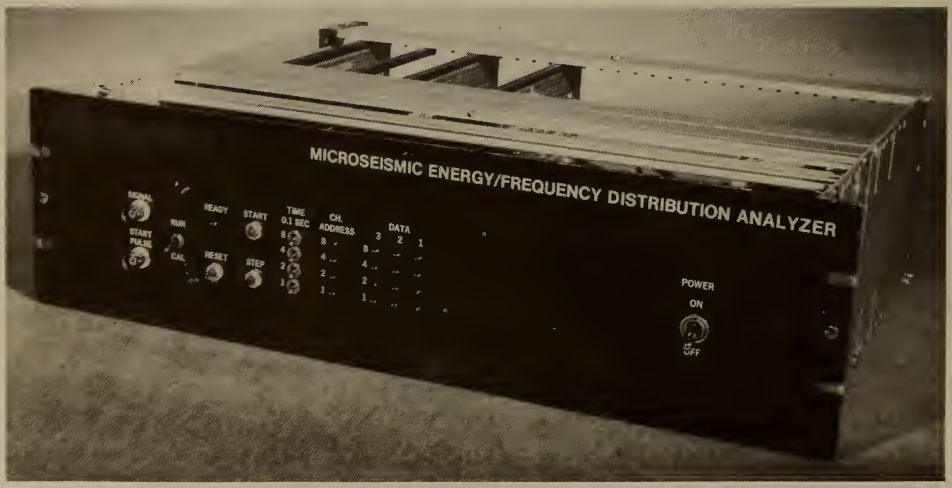


FIGURE 5. - Energy analyzer system.

microseismic application. The other sections are designed to show possible energy distribution shifts as failure processes progress. The filters roll off at about 24 dB per octave with ultimate attenuation in excess of 36 dB. The 100-Hz filter section will thus attenuate any 200-Hz components in the signal by 24 dB. These attenuations are obviously not infinite, but they are sufficient to separate significant energy and for frequency shifts for the microseismic applications for which they were built.

The outputs of the analog filters are alternating-current-coupled to an analog multiplexer with sample and hold. Each of the six analog filter outputs is then converted to a digital signal using a 10-bit analog-to-digital converter. The sample rates of the highest to lowest frequency filter output are 2^{13}, 2^{12}, 2^{11}, 2^{10}, 2^{9}, and 2^{8} samples per 0.1 s. Considering the filter bandwidth, it can then be seen that the frequencies in each filter section are sampled at the rate of 25.6 samples per cycle. The only exception to this is the full bandwidth section, which is sampled at 8.2 samples per cycle at its upper end. This timing, which at first may seem awkward, has a very logical basis. The basic system clock is 163,840 Hz so each of the sample rates can be obtained by a simple division by 2. The highest frequency channel gets sampled every 2d clock pulse (81,920 Hz), the next highest every 4th clock pulse, and this continues to form the previously mentioned sample rate. Similarly the integration segments can be normalized for direct comparison by simply shifting left. The rates are chosen this high so that the sampling interval is very short, making integrals obtained by simple addition very good representations of exact integrals. The sample and hold can acquire a 10-V signal change in 350 ns to 0.01-pct accuracy.

The analog-to-digital converter used in this system is a 12-bit unit, although only the 10 most significant bits are used in the calculation section. The signals from the filters are prescaled using voltage dividers so that the front panel input range is ±12 V. The maximum total throughput time of the analog-to-digital converter is 4 μs so it has no difficulty in maintaining the proper conversion rate for all six signal sections. The 10 bits that are used give a unipolar dynamic range of about 54 dB (9 data bits plus sign). This dynamic range and the real-time conversion speed are maintained throughout the subsequent signal processing. If extending the dynamic range were desirable, an obvious way to accomplish this would be to precision-rectify the analog signal and use the converter in a unipolar fashion. The sampling scheme maintains a constant sample time to signal period ($\Delta T/T$) ratio (fig. 6) at the band limit. The highest frequency in each filter section is sampled at the same rate. For this system this sampling method offers no real advantage other than ensuring that the higher frequency sections get sampled adequately. A disadvantage is that a signal whose frequency is low enough to allow it to pass through two or more filter sections will be sampled at diffferent rates in each section. This might yield slightly different energy results for the same signal. This problem is minimized because of the very high sample rates used in this system. If a set of bandpass filters had been used to break the spectrum into nonoverlapping segments that were

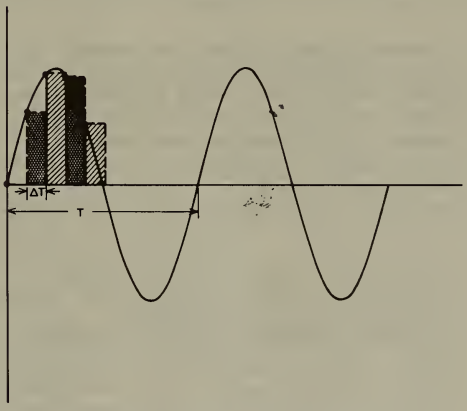


FIGURE 6. - Waveform digitization.

not continuous, the constant $\Delta T/T$ sampling would be necessary to ensure equal accuracy for all segments.

ARITHMETIC PROCESSING

The next step in the energy processing sequence is to square each digitized value. The original concept of the Bureau was to use one of the high-speed multiplier integrated circuits that have recently become commercially available. Rockwell's approach was to use a programable read only memory (PROM) look-up table. Both approaches are capable of the speed and dynamic range required. The Bureau's approach, however, offered much more flexibility since changes in word length and other system parameters could be easily accommodated. Using the Bureau's approach, the overall system operation would be simplified and accuracy improved as well. The Rockwell scheme is complex and can perhaps best be understood by referring to table 1. Rockwell uses the 10-bit analog-to-digital output to form the address selector for the PROM's. The PROM's serve as a look-up table for the squared values. Each unique 10-bit analog-to-digital output has a corresponding squared value stored in PROM. The table uses minus voltages for illustration since the plus voltages are represented by their binary complement because of the sign bit.

Rockwell chose to use the squared value rounded to the 16 highest bits in the PROM look-up table. The largest squared value that can be obtained with a 9-bit number is 18 bits, so some accuracy is sacrificed by rounding the 2 lowest bits. The Bureau's initial application calls for using only the 24 most significant bits of the 32-bit integrator output downstream at the squaring PROM's. The 2 least significant bits of the square then have no contribution to these 24 highest bits. The actual error in accuracy as a percent of full scale for typical signal levels is also insignificant in terms of a percentage of true value. A 0.4-V root root mean square (RMS) signal would be in error about 2 pct over a typical integration. It should, however, be clearly understood that this error is not inherent in this energy-measuring concept. It is an artifact of design decisions. If the Bureau's original concept of a 20 or more bit high-speed multiplier were used, or another 1,024 × 4-bit PROM were added, this error would be eliminated.

After being processed by the squaring PROM's, the digital value is shifted left to normalize it to compensate for the different sample rates. Each sample interval-amplitude level pair defines a rectangular box, which approximates the signal increment for each ΔT (fig. 6). Shifting the signals makes the rectangular box width equal for all filter sections. Mathematically each shift is a division by 2. For example, the 1,600-Hz section (ΔT = 24.4 μs) values are shifted once to provide an effective ΔT of 12.2 μs. Likewise, the 100-Hz section (ΔT = 390.6 μs) is shifted five times to provide an effective ΔT of 12.2 μs. Another way of looking at this is to realize that the 1,600-Hz section is sampled four times as often as the 100-Hz section so each of its samples is weighted at one-fourth the value of a 100-Hz sample as it is added to form the integral approximation of its respective section. This makes the energy numbers from the various sections directly comparable. For example, the energy numbers

TABLE 1. - Internal energy processing[1]

Input voltage	Analog-to-digital (sign bit removed)	Actual squared value	PROM output
-12.....	1111111(511_{10})	1111111100000000($261,121_{10}$)	1111111100000000(65,280)
-8.49....	101101001(361_{10})	1111111010001000($130,321_{10}$)	111111101000100(32,580)
-2.34....	001100100(100_{10})	10011100010000(10,000)	100111000100(2,500)
-.234....	000001010(10_{10})	0001100100(100_{10})	00011001(25_{10})

[1]Table is not exact because of rounding.

from each section for a signal of low enough frequency to pass through all sections will all be nearly equal, though the signal was actually sampled at different rates in each section.

The resultant 21-bit numbers from the shifter are then simply added for each respective filter section to provide the approximate integral of the squared signal (fig. 7). The maximum integration period selectable is 1.5 s. The adder is 32 bits wide to insure that no overflow will occur. Assume that the input was a sine wave at 6,000 Hz, 12 V peak-to-peak, and the integration period was 1.5 s. A sine wave has the property that the mean squared value is one half the peak value. The analog-to-digital converter would be full scale at the peaks. The average output of the squaring PROM would be $2^{16}/2$. The total number of samples of this average size would be 122,880. The output of the adder would then be 4,026,531,840, which is less than the full-scale output of the adder (2^{32}). The integration period, which can range from 0.1 to 1.5 s in 0.1-s increments, is selectable from front panel switches.

The Bureau uses only the 24 most significant bits of the adder output in the present microseismic application, as was mentioned in the squaring PROM discussion. Again it should be noted that this is not a limitation of the accuracy of the concept, only a design decision.

APPLICATION

The Bureau's Denver Research Center uses PDP 8/e data processors[3] in its rock burst-coal bump monitors. Since these processors have a 12-bit-wide bus, the upper 24 energy number bits are conveniently read in 2 words.

The rock burst monitor processes data from 24 channels, each of which is derived from a geophone at a unique location. One of these geophones is selected to be the energy channel. Its output is split between the rock burst monitor and the energy analyzer. Any active channel triggers the rock burst monitor. This trigger signal is then used to trigger the energy analyzer. A complication is introduced into this scheme since the rock burst monitor does not interrupt the computer unless certain valid event criteria are met within its logic. This by itself would leave the energy analyzer triggered on an invalid event and eventually ready to output invalid data. The Bureau modified the energy analyzer's original trigger circuits so that whenever a trigger occurs the energy analyzer is first reset and then triggered. This ensures that the energy analyzer and the rock burst monitor will both be processing the same event. Since the reset operation takes about 40 μs, a delay circuit was introduced (fig. 8) so that the energy unit first has time to reset before it is triggered into a processing mode. The Bureau also found it necessary to introduce hysteresis into the energy analyzer trigger circuit to avoid spurious noise triggers.

Initial fieldwork using the energy analyzer has begun. The original filters were changed to 6.4, 3.2, 1.6, 0.8, 0.4, and 0.2 kHz for the rock burst monitoring system, since this provided more information on the spectral distribution of these particular signals.

The motivation for this energy analysis stemmed from the promising application to ground failure prediction of the energy analysis done in the development of a roof fall warning system (4-5). Neither the energy analyzer nor the cruder techniques that preceded it have yet been successfully applied to rock burst prediction. The rock burst energy data are complicated by distance scaling effects, mine geometry effects, and rapid natural events mixed with manmade events during blasting. The scaling problem is being approached by taking ratios between the outputs of the various sections of the energy analyzer. The event-overlapping problem may be solvable by running the energy analyzer for fixed time intervals,

[3]Reference to specific products does not imply endorsement by the Bureau of Mines.

Channel	Filter, Hz	Sampling, rate, Hz	Shift
0	10,000	81,920	0
1	1,600	40,960	1
2	800	20,480	2
3	400	10,240	3
4	200	5,120	4
5	100	2,560	5

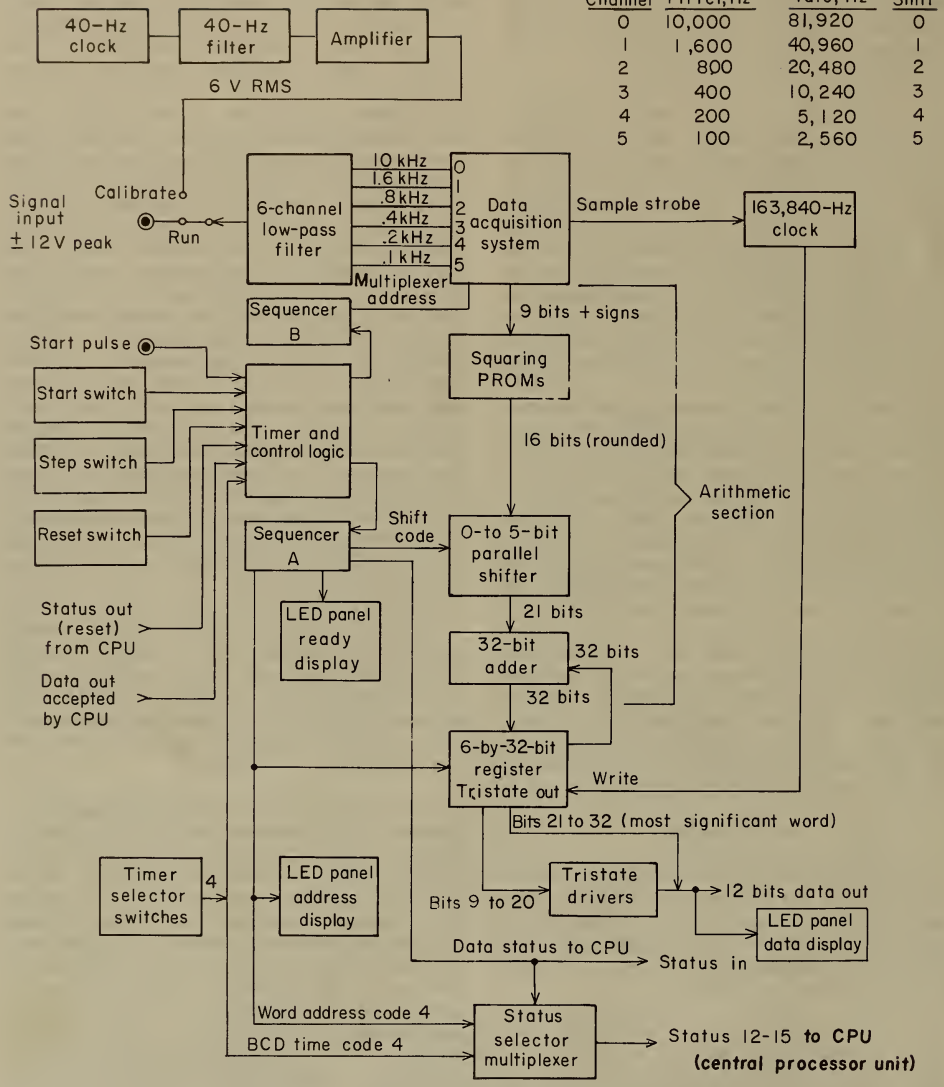


FIGURE 7. - Energy analyzer arithmetic processing.

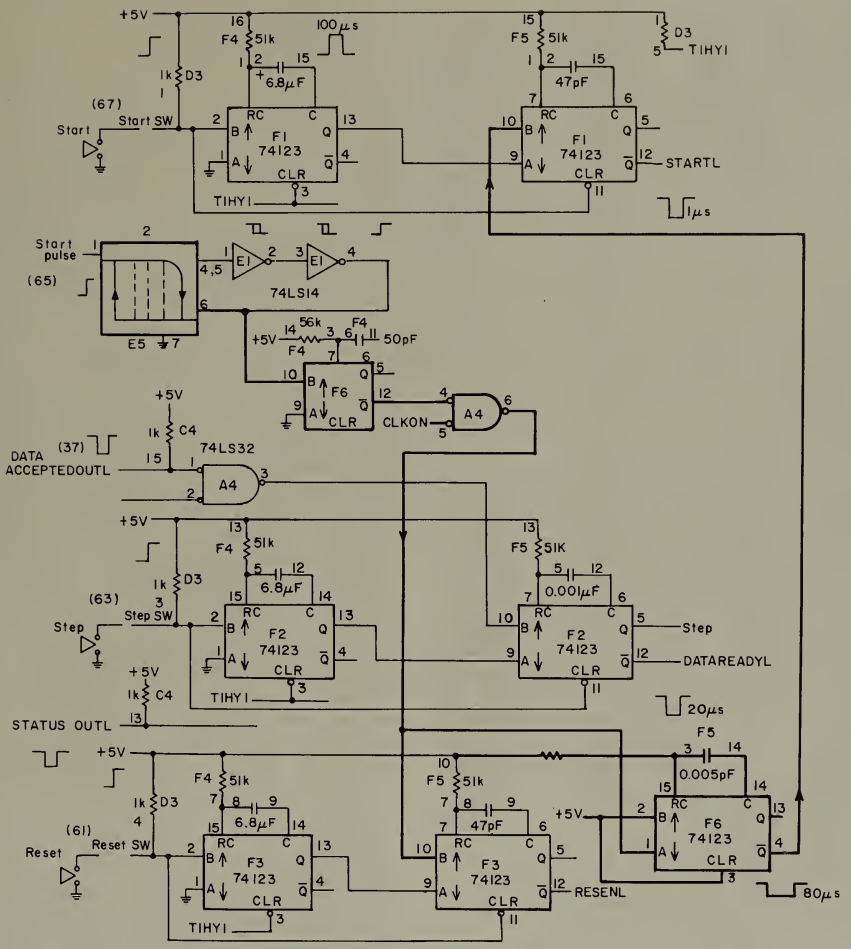


FIGURE 8. - Energy system circuit modifications.

similar to the approach used in the roof warning system, instead of trying to establish a separate energy for each event. The energy analyzer provides higher quality data than were previously available, but research must be done to maximize its benefit.

CONCLUSIONS

TAPE-TRIGGERING SYSTEM

A tape triggering and recording device has been designed, constructed, and tested. While individual parts of the overall performance are exceeded by other transient recording devices, the device is a significant advance in the state of the art in terms of the number of data channels, the data bandwidth, memory

length, transient capture, and digital record-reproduce technology as grouped in one instrument (6). Indeed, before recent advances in performance and reductions in cost of electronic circuits such as solid state memories, this device would have been impractical for industrial use (6). Since the trend in the electronics industry is toward a continuation of cost-performance improvement, the cost of similar units should drop while performance increases. Since the taped data are digitized, digital processing could be used as an alternate to, or in conjunction with, the present analog output. This device should have application in a wide variety of commercial recording problems.

ENERGY ANALYZER

The energy approximation produced by the energy analyzer is superior to those produced by any other devices the Bureau has used or examined. The hybrid digital technique of voltage-to-frequency conversion, for example, is limited because its frequency output varies with the amplitude of the voltage. Since the frequency output also indirectly sets an effective sample rate, each amplitude level is integrated with a differing degree of accuracy. At low amplitude, high signal frequency, the output can be a poor representation of the input integral. Analog techniques suffer from drift, limited accuracy, and limited dynamic range. The all-digital approach used in the energy analyzer is a significant step forward in real-time energy processing. It is, however, recognized that at frequencies less than about 40,000 Hz, fast Fourier transform analyzers would provide a more detailed real-time energy analysis. The concept of the energy analyzer was to solve, in principle, the problem of real-time energy estimation throughout the range of frequencies used by acoustic emission researchers at a reasonable cost. With the present availability of video frequency analog-to-digital converters and very high speed digital multipliers, it is felt that this has been accomplished. The motivation for a concise, few-number energy estimate stems from the Bureau's research in microseismic roof fall warning systems (4-5). It has been found that having an approximate energy figure may be a key to being able to assess the stability of the rock mass. Often, for the Bureau's real-time stability assessments, a complete spectrum would be too much information. It is desirable to have a simple, compact means of presenting energy information to the on-site engineer. The energy analyzer and the principles it embodies provide a means for obtaining a good energy estimate that satisfies these criteria.

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